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14. ABSTRACT

Abstract—World wide more than 400 aquatic systems are hypoxic, affecting an area of more than 245,000 square kilometers. The hypoxic area in Gulf of Mexico is the second largest in the world next to the Baltic Sea basin. In the northern Gulf of Mexico hypoxia is a phenomenon which occurs when the seasonal thermohaline stratification in the water column develops. Under normoxic or hypoxic conditions benthic organisms affect the physicochemical properties of sediment by their usual biological activity such as feeding, locomotion, and burrowing. According to the Pearson-Rosenberg model,

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Benthic Community Response to Hypoxia: Baseline Data

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Abstract*—World wide more than 400 aquatic systems are hypoxic, affecting an area of more than 245,000 square kilometers. The hypoxic area in Gulf of Mexico is the second largest in the world next to the Baltic Sea basin. In the northern Gulf of Mexico hypoxia is a phenomenon which occurs when the seasonal thermohaline stratification in the water column develops. Under normoxic or hypoxic conditions benthic organisms affect the physicochemical properties of sediment by their usual biological activity such as feeding, locomotion, and burrowing. According to the Pearson-Rosenberg model, changes in the benthos due to hypoxia occur at the community level of organization, with the pioneering community having different biological behavior than the equilibrium community, which normally exists without hypoxic stress. These changes as a response to low oxygen include numerical density, species diversity, organism size, depth of bioturbation, and number of functional groups—all factors which ultimately can affect the physicochemical properties of sediment. Thus, to some extent there may be a feedback mechanism that conditions the sediment properties for the particular type of benthic community. The types of sediment properties that can affect the density and diversity of benthos include grain size distribution, bulk density, and concentration of organic matter. To study these changes, macrobenthos and sediment samples were collected from the northern Gulf of Mexico between the Atchafalaya and Mississippi Rivers. Four provinces were chosen based on the frequency of occurrence of hypoxic events for a comparison between pre-hypoxic conditions in early spring and hypoxic conditions in late summer. The macrobenthos data will be compared with the sediment properties of grain size, organic matter concentration, sedimentation rate, and depth of the redox potential discontinuity to help explain the variability in the biological data among provinces. The macrobenthos data will be statistically analyzed for species richness using Hurlbert rarefaction curves that enable the calculation of the richness for a set number of species, organism sizes, bioturbation depths, and functional groups. The macrobenthos data will be correlated with sediment properties using the principal component analysis. These baseline data will be compared with similar data collected in September for assessing the effects of hypoxia on benthic community structure in the northern Gulf of Mexico.

1. INTRODUCTION

Hypoxia is an emerging environmental problem around the world [1]. The northern Gulf of Mexico is one among approximately 400 hypoxic zones, the second largest in terms of geographical area in the world, and the largest in America [2]. An aquatic environment is defined as hypoxic when the bottom water dissolved oxygen concentration drops below 2 mg/l, a concentration that is detrimental to most benthic invertebrates. Therefore, benthic organisms may be used as bioindicators of the oxygen stress level of the environment in which they live.

The development of hypoxia in the northern Gulf of Mexico is promoted by the confluence of two events: the discharge of nutrient-rich freshwater from the Mississippi River and the density stratification induced by temperature and salinity in the water column that isolates the bottom water [3]. During the summer months, warmer, less dense surface water will become an effective barrier to mixing of oxygenated surface water with the denser oxygen-depleted bottom water. Water rich in the nutrients nitrogen and phosphorus will trigger an increase in primary production realized as a phytoplankton bloom. When the phytoplankton die and sink to the sea bottom they undergo bacterial decomposition which requires oxygen. The conventional explanation indicates that the biological oxygen demand from the decaying phytoplankton leads to the reduced oxygen concentration in the bottom water. Other factors that contribute to the development and maintenance of bottom water hypoxia are current pattern, nutrient concentration in the overlying water column, quality of organic matter reaching the sea floor, and oxygen consumption rates in the water column and in the benthos [3]. The bottom water in the northern Gulf of Mexico develops hypoxia generally during the end of spring and continues throughout the summer months. Bottom water oxygen concentration starts to recover during the fall and winter months as the water temperature decreases and the thermohaline stratification in the water column disappears as a result of vertical mixing in the water column.

The first event of hypoxia in the northern Gulf of Mexico to be measured was in 1972 [4], but the systematic, shelf-wide measurement of hypoxia did not begin until 1985. From the sedimentology of the Gulf of Mexico it is compellingly evident that hypoxia was present before the late 1940's, when the use of fertilizers increased [4]. The maximum area of hypoxia measured since 1985 is 22,000 km^2 during 2002 [5]. Hypoxia is a recurring annual event in the northern Gulf of Mexico, but its temporal and spatial extent varies every year [4]. This necessarily means that various areas of the sea floor are exposed to hypoxia for different amounts of time. This creates a natural exposure

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gradient over which the effects of hypoxia on benthos and sediment can be measured.

It is well documented that, under normoxic conditions sediment and the animals living in there influence each other to create a unique community structure [6]. Sediment properties such as grain size distribution, organic matter concentration, dissolved oxygen concentration, and redox potential discontinuity depth are some sediment characteristics that can determine the benthic community structure. However, the animals living in the sediment can change the physicochemical properties of sediment such as permeability, porosity, erodibility, shear strength, and redox potential discontinuity depth by feeding, locomotion, and burrowing [7]. When dissolved oxygen concentration is depleted from the bottom water and hypoxia develops, the benthic community structure changes; also the behavioral response of the fauna changes [8]. This effect is more pronounced near the source of the organic enrichment (river mouth) and reduces progressively away from it [8]. The area near the source where the oxygen is low and organic matter deposition is high is colonized by a few small size organisms. There vertical distribution of organisms within sediment is usually limited to the uppermost layer of the sediment as result of reduced depth of the redox potential discontinuity [9]. The depth of the redox potential discontinuity increases as the distance from the source increases and the area is colonized by the more diverse, large-size organisms with larger and deeper burrows [9].

II. Methods

Sediment and benthic macrofauna samples were collected from the northern Gulf of Mexico between the Atchafalaya and Mississippi Rivers. Four provinces were selected within a depth range of 30 to 50 m between these rivers. The provinces were selected based on the frequencies of hypoxia occurrence that were derived from yearly monitoring of bottom water oxygen concentration since 1992 by the Louisiana Universities Marine Consortium. The normoxic province (hypoxia occurring less than 25% of the time) was the westernmost location. The hypoxic, briefly hypoxic, and frequently hypoxic provinces (in which hypoxia occurs more than 25% of the time) were arrayed to the east of the normoxic province.

In each province six box cores were collected, either as three pairs at the vertices of a 1-km-on-a-side triangle (hypoxic provinces), or as two groups of three at the center and lower right vertex of the triangle (normoxic province). Sediment samples were collected using 0.25-m^2-area box corer. Three 8.2-cm-diameter subcores were collected from each box core. Each subcore was cut into 9 or 10 sections at intervals of 0-1 cm, 1-2 cm, 2-4 cm, 4-6 cm, 6-8 cm, 8-10 cm, 10-15 cm, 15-20 cm, 20-25 cm and 25-30 cm depth in the sediment core. These samples were sieved through a 300-µm nitex mesh and the macrofauna retained on the mesh were fixed in 5% formalin-seawater solution at sea and preserved in 70% isopropanol in the laboratory. The macrofauna samples were sorted and identified to species to determine abundance, biomass, and species diversity as well as their vertical distribution within the sediment.

In addition to the macrofauna cores, three 5.9-cm-diameter subcores were collected from the same box core for the purpose of analyzing the radiochemical, organic matter, physical and acoustic properties of the sediment. Organic matter analysis was performed at the USM Department of Marine Science. Sedimentary organic carbon (POC) concentrations were determined for subcores from all four provinces by diluting $\approx$1 g of sample with dilute HCl (2 N) and heating on a hotplate. Samples were rinsed in triplicate to ensure that no inorganic carbon remained. Samples were then run in triplicate on a Perkin Elmer Series 2400 Elemental Analyzer (CHNS/O) using standard methods to determine POC [10],[11].

TABLE I

Coordinates and Water Column Depths for the Stations at the Four Provinces from which the Samples were Collected

Provinces	Stations	Latitude	Longitude	Depth (m)
NO	2	28° 39.2977'N	92° 22.8130'W	37.1
	4	28° 39.3607'N	92° 22.9550'W	
HO	2	28° 36.4785'N	91° 14.4120'W	29.9
	3	28° 36.2695'N	91° 14.2355'W	
	4	28° 36.2270'N	91° 14.5785'W	
BH	2	28° 30.1620'N	90° 50.0145'W	31.9
	3	28° 29.9040'N	90° 49.8660'W	
	4	28° 29.9050'N	90° 50.1910'W	
FH	2	29° 00.7180'N	89° 44.9290'W	39.1
	3	29° 00.4470'N	89° 44.8325'W	
	4	29° 00.4595'N	89° 45.1560'W	

III. Results

Samples were taken from four different provinces and three stations were selected from each province except the NO province (Table I). Instead, two stations were selected from NO province and three box cores were collected from each station. Three subcores were collected from each box core. For the results presented here, one box core was selected from each station and sieved, vertically sectioned samples from three subcores from that box core were sorted and the fauna identified to phylum level. The variations between the provinces and the within the provinces are presented in Figs. 1-5.

The samples were represented by six different phyla, namely Annelida, Sipuncula, Arthropoda, Cnidaria, Mollusca and Echinodermata (Table II). The phylum Annelida was solely represented by polychaetes and the phylum Cnidaria was represented solely by hydroids. However, the phylum Mollusca was represented by bivalves, gastropods and scaphopods. The phylum Arthropoda was solely represented by the Crustacea: amphipods, isopods, decapods and stomatopods. The

category "miscellaneous" was comprised of small fishes, unidentified worm-like fauna, and invertebrate larvae. Annelida is the dominant phylum, followed by Mollusca, over the entire study area. The average abundance was highest in BH province (19,139 ind./m^2), followed by NO province (18,067 ind./m^2), HO province (13,216 ind./m^2), and FH province (7050 ind./m^2).

TABLE II
NUMBERS OF ORGANISMS PER M^2 AT EACH STATION

NO	NO4A	NO2B		Total
Polychaeta	4906.2	7359.3		12265.5
Sipuncula	265.2	265.2		530.4
Mollusca	2917.2	2917.2		5834.4
Hydroida	66.3	464.1		530.4
Crustacea	464.1	1922.7		2386.8
Echinodermata	—	331.5		331.5
Miscellaneous	10541.7	3712.8		14254.5
HO	**HO2A**	**HO3A**	**HO4A**	**Total**
Polychaeta	6364.8	11005.8	8884.2	26254.8
Sipuncula	—	—	—	—
Molluscs	198.9	861.9	1259.7	2320.5
Hydroida	66.3	—	132.6	198.9
Crustaceans	—	66.3	331.5	397.8
Echinoderms	132.6	132.6	729.3	994.5
Miscellaneous	663.0	6696.3	2121.6	9480.9
FH	**FH2A**	**FH3A**	**FH4A**	**Total**
Polychaeta	3712.8	7690.8	3116.1	14519.7
Sipuncula	—	—	—	—
Mollusca	—	1127.1	397.8	1524.9
Hydroida	—	—	—	—
Crustacea	—	—	—	—
Echinodermata	—	—	—	—
Miscellaneous	861.9	331.5	3911.7	5105.1
BH	**BH2B**	**BH3B**	**BH4B**	**Total**
Polychaeta	10674.3	12530.7	8022.3	31227.3
Sipuncula	—	132.6	530.4	663.0
Mollusca	2386.8	2187.9	663.0	5237.7
Hydroida	—	198.9	132.6	331.5
Crustacea	331.5	397.8	132.6	861.9
Echinodermata	729.3	265.2	530.4	1524.9
Miscellaneous	5635.5	6033.3	5900.7	17569.5

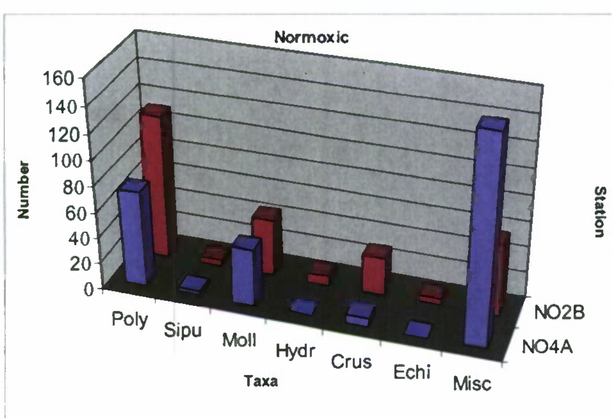

Figure 1. Abundance of different taxa from two stations of the normoxic (NO) province.

The samples collected from the NO province were intended to represent a benthic community rarely exposed to hypoxia. The nature of the sediment was sand-silt-clay with significant amount of shells and shell hash [12]. Samples from the two stations NO2B and NO4A contain representatives of all six major taxonomic groups found from all four provinces (Fig. 1). Polychaeta was the dominant group, followed by Mollusca and Crustacea. The remaining phyla were represented as sparse and equally abundant, although in station NO4A representatives of phylum Echinodermata were absent. The station NO4A has a larger abundance of organisms per unit area compared to the other station that was sorted (NO2B).

The samples collected from the HO province were intended to represent a benthic community regularly exposed to hypoxia over the last 20 years. The sediment at this province was a sand-silt-clay [12]. Samples from the three stations HO2A, HO3A, and HO4A contained five groups out of the six taxonomic groups found in this study (Fig. 2). The polychaetes were dominant at all stations, followed by mollusks and echinoderms. The phylum Sipuncula was completely absent in this province. Station HO3A has the highest abundance of organisms per unit area, followed by HO4A, and then HO2A.

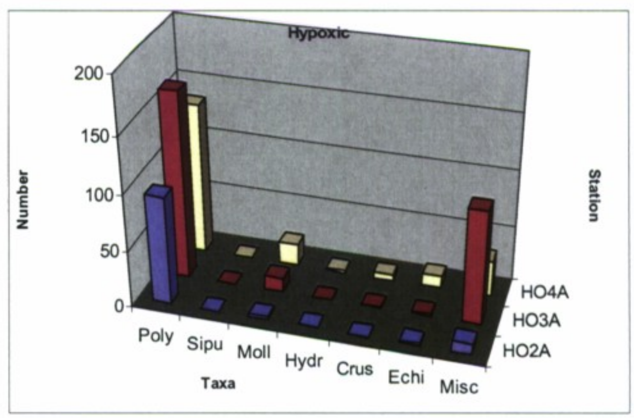

Figure 2. Abundance of different taxa from three stations of the hypoxic (HO) province.

The samples collected from the FH province were intended to represent a benthic community recently exposed to hypoxia. The nature of the sediment was silty clay [12]. Samples from the three stations FH2A, FH3A, and FH4A contained two groups out of the six identified taxonomic groups (Fig. 3). Polychaetes were the dominant taxa at all three stations, followed by mollusks. The other four taxa were absent in this province. Station HO3A has the highest abundance of organisms per unit area, followed by HO4A, and then HO2A.

The samples collected from the BH province were intended to represent a benthic community less recently exposed to hypoxia. The type of sediment was sand-silt-clay [12]. Samples from the three stations BH2B, BH3B, and BH4B

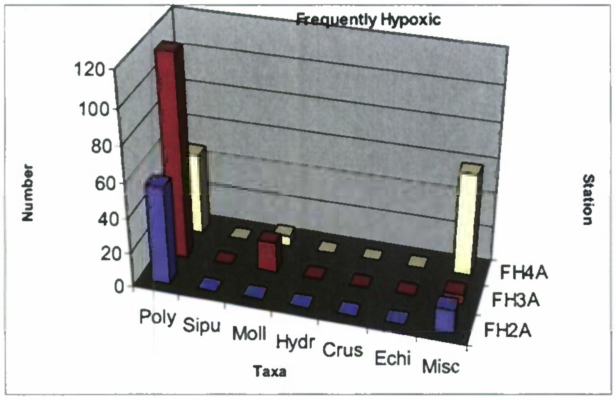

Figure 3. Abundance of different taxa from three stations of the frequently hypoxic (FH) province.

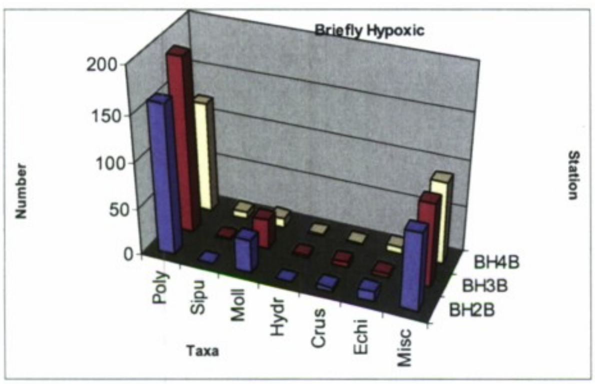

Figure 4. Abundance of different taxa from three stations of the briefly hypoxic (BH) province.

contained all six identified taxonomic groups (Fig. 4).

Polychaetes were the dominant taxa at all three stations, followed by mollusks, echinoderms, crustaceans, sipunculids and hydroids. Station BH3B has the greatest abundance of organisms per unit area, followed by BH2B, and then BH4B. The stations examined from the BH province have the least variability among stations within a province.

Polychaetes dominate in terms of abundance, followed by mollusks, over all stations in every province (Fig. 5). The average abundance was highest in BH (19,139 ind./m^2), followed by NO (18,067 ind./m^2), HO (13,216 ind./m^2), and FH (7050 ind./m^2). These are preliminary data, and are not considered to be statistically significant at this time.

The average organic carbon percentage in the provinces NO, HO, and BH is 0.04%, reaching a minimum value of around 0.02% at 1.5 to 4 cm sediment depth (Fig. 6). The maximum organic carbon percentage in the province HO is 0.07% at the sediment surface. The average organic carbon percentage in the province FH is much greater than the other three provinces (0.15%) and has a maximum value of 0.16% at the sediment surface. The percent carbon concentration reaches a minimum within the same depth as observed storm layers [12],[13]. It is likely that winnowing of easily suspended organic matter has occurred during the suspension and settling of sediments during the storm.

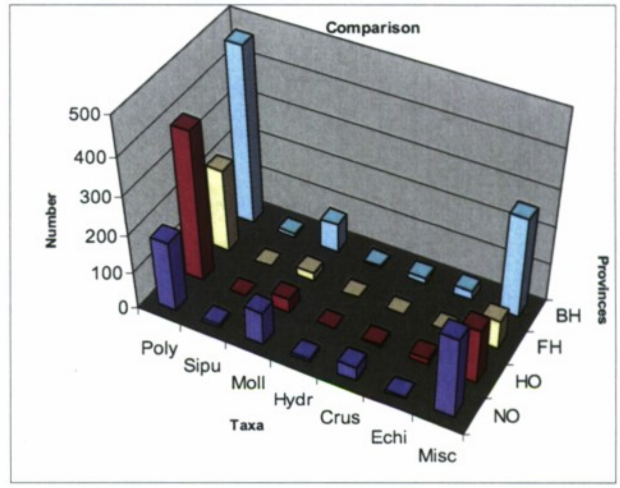

Figure 5. Abundance of different taxa in NO, HO, FH, and BH provinces.

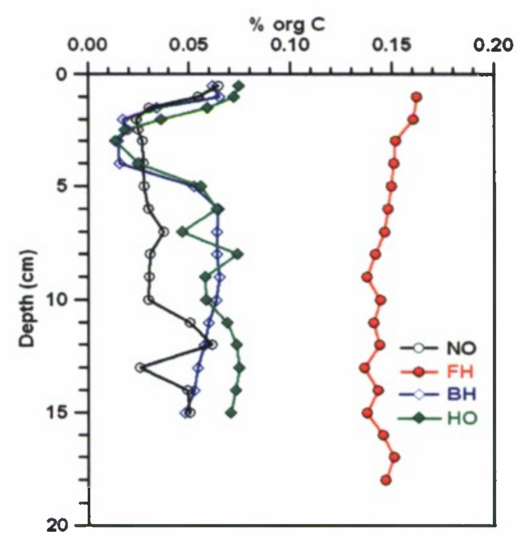

Figure 6. Vertical distribution of percent organic carbon in sediment samples from NO, HO, FH, and BH provinces.

The average organic nitrogen percentage in the provinces NO, BH, and HO is about 0.005% with maximum value of 0.009% at the sediment surface (Fig. 7). The average organic nitrogen percentage in the province FH is much higher (0.017%) with maximum value of 0.019% at the sediment surface and minimum value of 0.016% at 13 cm depth. The organic nitrogen percentage at province FH is relatively unchanged down to 18 cm sediment depth. These results, including minima occurring at 1.5 to 4 cm sediment depth, are consistent with the data from the organic carbon analysis.

The average C:N ratio for the four provinces is around 10.0 (Fig. 8). Province NO has an anomalous C:N value of 23.9 at 12 cm sediment depth, which may be an indication of buried

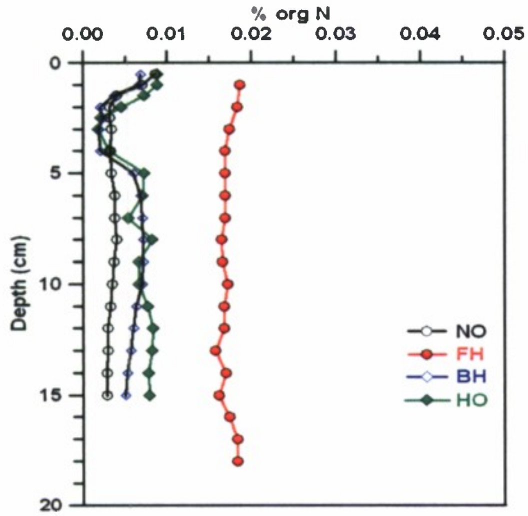

Figure 7. Vertical distribution of percent organic nitrogen in sediment samples from NO, HO, FH, and BH provinces.

refractory organic matter. The C:N ratio reaches a minimum value of 8.7 at the sediment surface, where the freshest organic matter has settled. The average C:N ratio for the province HO is 10.0 with maximum value of 11.0 at 14 cm depth and minimum value of 8.86 at 3cm depth. The average C:N ratio for the province FH is 9.98 with maximum value of 10.45 at 2cm depth and minimum value of 9.36 at 15cm depth. The average C:N ratio for the province BH is 10.51 with maximum value of 11.58 at 14cm depth and minimum value of 8.80 at 4cm depth. Out all four provinces NO has highest C:N ratio followed by BH, HO, and FH.

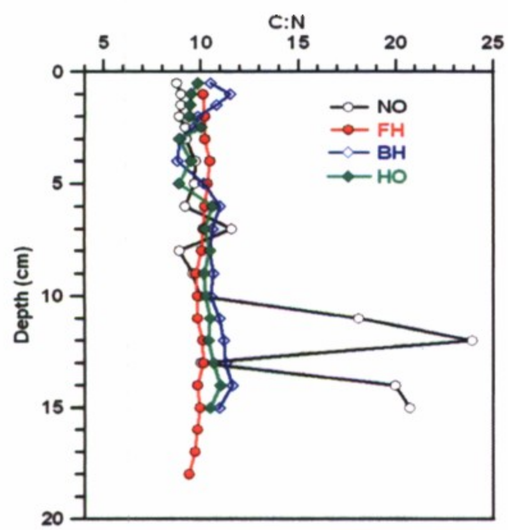

Figure 8. Vertical distribution of the C:N ratio within the sediment samples from NO, HO, FH, and BH provinces.

IV. Discussion

The effect of hypoxia on benthos has been well document throughout the world, including the northern Gulf Of Mexico [14],[15]. The distribution of benthic organisms is influenced by the physical environmental factors such as water column depth, currents, and sediment type [16]. To sample the same community and to assess the impact of hypoxia on the community our samples were collected with in 30 to 40 m water depth with similar sediment types.

Our results show that generally, a sea floor with a sand-silt-clay and lower percentage organic carbon and organic nitrogen content in the sediment shows higher abundance and species diversity compared to a sea floor with a silty clay and higher percentage organic carbon and organic nitrogen content. Province FH had fewer numbers of organisms and lower species diversity. The likely reason for the higher percentage organic carbon and organic nitrogen content and finer sediment in FH province is that this province is very close to the river mouth and it is exposed to higher loading of organic matter compared to the other provinces. As a result its sea floor has a low-density and fluffy sediment. [12]

Polychaetes are the major contributors of the benthic biomass in all the stations of all four provinces. The other taxa representing the benthic populations were bivalves, gastropods, scaphopods, amphipods, isopods and stomatapods. These biological data are corroborated in terms of the same taxa in the same region during 1979 to 1981. [17]

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